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Climate change impact on Canada's Pacific marine ecosystem: The current state of knowledge

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ABSTRACT

Global warming is already affecting the oceans through changes in water temperature, acidification, oxygen content and sea level rise, amongst many others. These changes are having multiple effects on marine species worldwide, with subsequent impacts on marine fisheries, peoples' livelihoods and food security. This work presents a review of the recent literature on the current and projected impacts of climate change on Canada's Pacific marine ecosystem. We find that there is an increasing number of studies in British Columbia focusing on changes in ocean conditions and marine species responses under climate change, including an emerging literature on the socio-economic impacts of these changes considered to be a knowledge gap. According to the literature, it is well established that ocean temperatures are increasing over the long-term, especially, in southern areas of British Columbia. Warming trends are increasing in the spring and are strongest in summer. However, there are important uncertainties regarding other climate drivers, such as oxygen concentration and acidification, stemming mainly from the insufficiency of data. Pacific salmon, elasmobranchs, invertebrates and rockfishes are amongst the most vulnerable species groups to climate change in British Columbia. Also, shifts in stock distribution and fish abundance under climate change may have a significant impact on fish supply affecting the livelihoods and food security of some British Columbians. The magnitude of these impacts is likely to vary according to a latitudinal gradient, with southern coastal areas being more affected than northern and central areas; challenging multiple areas of governance, such as equity and fishing access amongst First Nations; and institutional arrangements for transboundary stocks between the U.S. and Canada.

1. Introduction

The socio-economic contribution of global fisheries to human society is undeniable [1–3]. The fishing sector itself provides more than 3 billion people with 20% of their average annual per capita protein intake [4], and generates global revenues above USD 100 billion annually [5,6]. Moreover, global fisheries benefit more than 56 million fishers globally, and provide direct and indirect support for the livelihood of 12% of the worlds' population [4]. In particular, small-scale fisheries worldwide provide important source of jobs and income for the subsistence of many coastal communities [2,3].

Despite growing awareness of the essential ecosystem services that oceans provide to nature and society, human stressors have continued to negatively impact species and marine habitats [7]. Overfishing, pollution, and anthropogenic climate change (CC) are challenging the current capacity of marine population to thrive [8–11]. For example, anthropogenic CC, is impacting marine organisms through changes in ocean conditions, such as temperature, oxygen, salinity, pH, currents, and primary production [12–14]. Marine species responses to shifting climate conditions include changes in growth and body size, changes in species distribution and timing of phenological events [15,16], impacting population abundance and productivity.

The effects of CC on marine life may have significant consequences for fisheries, people's livelihood and food security [2,14]. Global studies have projected large changes in future catch distribution [17] and fisheries revenues [18] across a latitudinal gradient, with the potential to impact fishing costs, fishers' incomes, and household incomes [2,19]. Moreover, CC effects on fish stocks will impact national economies and food availability, especially, in fish-dependent countries with low adaptive capacity [20]. Therefore, it is important to understand how all these changes are manifesting at the local level.

Since the 1990s, there has been a growing scientific literature on the west coast of Canada, addressing shifting ocean conditions and changes in

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marine organisms and fisheries due to climate variability [20–23]. In the past two decades, the number of scientific articles studying these areas have multiplied. Many of this knowledge have been synthesized by Okey et al. [25,26], which provides a comprehensive review of CC effects on Canada's Pacific marine ecosystems. Okey et al. [26]'s review incorporates knowledge from the 4th IPCC report (2007), local assessments from Fisheries and Oceans Canada (DFO), and modelling studies that forecast CC effects on marine ecosystems, covering a wide range of subject areas, such as, oceanography and climate conditions (e.g., temperatures, hydrology, salinity, oxygen, pH, sea level), marine life (e.g. species distribution, community composition, occurrence of new species), fisheries responses, and marine habitat vulnerability. Since Okey et al. [26], the state of knowledge in this area has increased further, with the publication of the 5th IPCC report (2013) and new scientific articles on the region, including emerging topicson issues, such as socio-economic and vulnerability analysis of CC impacts [27–29].

This study aims to update and extend Okey et al. [26] by reviewing relevant articles published between 2014 and 2017, as well as studies on the socio-economic and governance dimensions of CC in the region. Having a better understanding of the current and predicted impacts of climate change in Canada's Pacific Ocean, can help us identify the main risks that fisheries, communities and the economy are facing in the region due to CC, and improve conservation plans to protect marine species from climate variability at the local level. Ultimately, this can provide the basis for the design of adaptation strategy for fishers, fishing enterprises, coastal communities and municipalities to help them cope with global warming effects in the region.

2. Methods

To update the existing reviews of the current and predicted impact of climate change in Canada's Pacific marine ecosystem and fisheries, we conducted a systematic literature review guided by seven different topics and research questions that capture the biophysical and socio-economic components of climate change effects on Canada's Pacific Ocean (Table 1). The literature search was conducted for the period 2014–2017, although, the review includes some literature from previous years, which contrast or support the current findings. The main search includes material from governments in the form of technical reports and scientific publications; non-governmental organizations (e.g., local assessments); and academic sources, such as scholarly journals, books and thesis.

Each search was conducted by combining multiple topics (Table 1) and databases that covered natural and social science disciplines (Table 2). In turn, the topics were represented by sub-themes and keywords —over 350 words in total— (see Supplementary Information). For example, biochemistry is a sub-theme identified for Search 2, which was represented by keywords such as "ocean biochemistry" or “nutrients” or "carbon cycle" or "nitrogen cycle". To refine the search, these keywords were entered in the Advanced Search setting and combined with Search 1, which captured climate change drivers, marine species of BC and geographical areas of Canada's Pacific marine ecosystems. Thus, each search includes the topics A, B and C (e.g., Search 1) as a basis to narrow down all the subsequent set of searches. Finally, boolean operators (e.g., AND, OR, NOT) were used to combine searches and refine the results.

Each search was refined by publication date covering the period 2014–2017, country or region (e.g. ,Canada/North America), excluding subject areas with no direct connection with the topic, such as, science technology, forestry, energy, fuels, etc. A further refinement of the results was conducted by scanning titles and abstracts, excluding non-pertinent information and duplicates between searches, as several studies related to Search 2 could be found in Search 3, as well, and vice versa. The resulting articles were also rearranged according to their corresponding topics, after excluding repeated articles between library databases. Articles covering more than one subject area, e.g., vulnerability, risk assessments, or comprehensive reviews, were included in the species responses topic, and therefore are not repeated in other topics (see Fig. 1).

Ultimately, we present a summary table that captures different components of vulnerability and risk assessments, such as sensitivity and adaptive capacity of marine species, as well as, climate change impacts on species and fisheries of BC. Along with presenting scores for each component, we summarize the main finding of multiple assessments synthetizing the overall knowledge about how BC fisheries resources are vulnerable to CC (Section 3.5.). The summary table has five main columns with scoring from each assessment on eighty-eight marine species in BC (Table 5a,b,c).

Three assessments have actual numerical scores [i.e., Hunter et al. [30]; Jones and Cheung [31]; Weatherdon et al. [29]](see Supplementary Information). We provide our own scores and metric for those assessments that do not have them (e.g., Okey et al. [26]; Haigh et al. [32]). The criteria used to assign scores was different for both assessments. For example, Haigh et al. [32] present a summary table with ocean acidification (OA) effects, expressed with the following categories: likely positive, likely neutral, likely negative, possibly negative (low certainty) and unknown. However, positive and neutral effects were not represented in our metric as these effects are mainly found in phytoplankton and zooplankton species, which are not covered in this paper. On the other hand, we decided to include two additional categories (i.e., likely indirect negative effect; possibly indirect negative effects) to capture significant information related to indirect effects of

Table 1
Guiding topics and research questions of the literature review.

TOPIC		QUESTIONS	SEARCH
A	Climate change drivers	What are the drivers of global climate change	**1**
B	Marine species of British Columbia (BC)	What are the main marine species in BC	**1**
C	Canada’s Pacific marine ecosystem	How Canada’s Pacific marine ecosystem areas are defined	**1**
D	Ocean conditions	How CC is affecting ocean conditions (physics, chemistry) in BC	**2**
E	Physiology and ecology of marine species	How CC is affecting marine species (physiology, ecology) in BC	**3**
F	Socio-economic	How CC is affecting marine fisheries (e.g. catches, revenues)	**4**
G	Governance/management	How CC is affecting fisheries management (e.g. adaptation, policy)	**5**

Table 2
Search number and topics by library databases.

SEARCH	TOPIC	Web of Science Core Collection	ASFA - Aquatic Sciences & Fisheries Abstracts	PAIS Index	Fisheries and Oceans Canada Library (DFO)	EconLit	Google Scholar[a]
1	**A, B, C**	✓	✓	✓	✓	✓	✓
2	**A, B, C, D**	✓	✓	✓	✓	✓	X
3	**A, B, C, E**	✓	✓	✓	✓	✓	X
4	**A, B, C, F**	✓	✓	✓	✓	✓	X
5	**A, B, C, G**	✓	✓	✓	✓	✓	X

[a] Only Search 1 was run in Google Scholar due to search engine constraints (e.g. combination of multiple searches is limited).

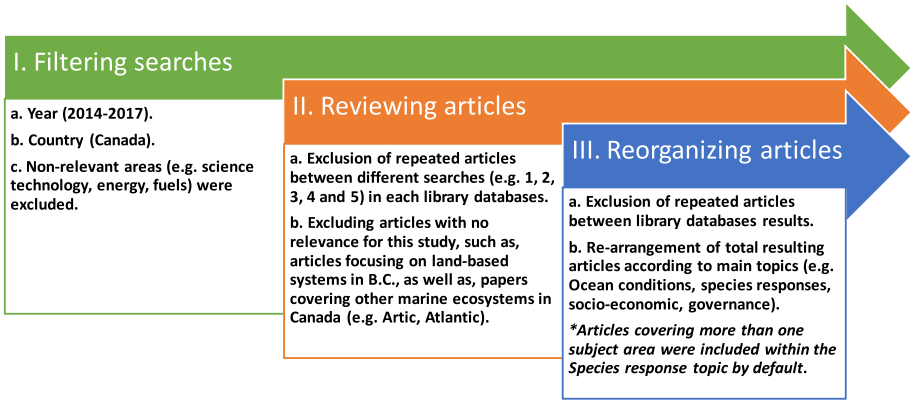

I. Filtering searches
a. Year (2014-2017).
b. Country (Canada).
c. Non-relevant areas (e.g. science technology, energy, fuels) were excluded.
II. Reviewing articles
a. Exclusion of repeated articles between different searches (e.g. 1, 2, 3, 4 and 5) in each library databases.
b. Excluding articles with no relevance for this study, such as, articles focusing on land-based systems in B.C., as well as, papers covering other marine ecosystems in Canada (e.g. Artic, Atlantic).
III. Reorganizing articles
a. Exclusion of repeated articles between library databases results.
b. Re-arrangement of total resulting articles according to main topics (e.g. Ocean conditions, species responses, socio-economic, governance).
*Articles covering more than one subject area were included within the Species response topic by default.

Fig. 1. Filtering process for literature selection.

Table 3
Main characteristics of vulnerability and risk assessments (See Section 3.5.).

	Okey et al. [26]	Hunter et al. [30]	Jones and Cheung, [31]	Weatherdon et al. [29]	Haigh et al. [32]
Assessment Type	Sensitivity (Species responses)	Sensitivity (Life history)	Impact Biology/ecology	Impact (Catch potential)	Impact (Ocean acidification)
Research Method	Literature/ expert-based	Literature/ expert-based	Model-based (Fuzzy logic)	Model-based (DBEM)	Literature/ expert-based
Climate Stressors	Temperature, pH, waves, oxygen, currents, precipitation	Temperature, currents, pH, food webs	Temperature, oxygen and pH	Temperature, salinity, sea ice concentration	pH
Species	34	43	48	56	47
Scoring Method	Rank score	Rank score	Index value	Rate of change	Ordinal scale
Scale	50-700	3-9	1-100	100 - (-100)	1-100
Score labels	50-149 ; Low 150-349 ; Medium 400-700 ; High	3.74-4.5 ; Low 4.75-5 ; Medium-low 5.25-5.5 ; Medium 5.75-6 ; Medium-high 6.25-6.5 ; High	1-24 ; Low 25-74 ; Medium 75-99 ; High 100 ; Very high	100 - (-9) ; Low -10 - (-24) ; Medium -25 - (-49) ; High -50 - (-100) ; Very high	1-24 ;Low 25-49 ;Medium 50-74 ;Medium-high 75-100;High

OA on marine species available in Haigh et al. [32].

In the case of Okey et al. [26], we created a scoring framework to score distinct types/degrees of CC manifestations, as well as, responses of marine species to shifts in ocean conditions (see Supplementary Information). Both scorings were then summed to obtain an overall sensitivity score for each species. Overall scores also accounted for information on species impacted by more than one climatic stressor or by non-climatic stressors (e.g., overfishing and pollution) given that descriptions of climatic forcing are often associated with non-climatic conditions. We assigned negative values to those species positively affected by environmental changes to counteract their negative effects.

Sensitivity and impacts scores were organized into different set of categories (e.g., low, medium-low, medium, medium-high, high, very high) available in Table 3, and are expressed as such, in the main summary table (for numerical scores see Supplementary Information).

Because the framework, scope and metric used by each assessment are different, the results are not comparable across the columns (see Table 3). Assessment of CC impacts focus on the effects of environmental stressors, which includes multiple climate drivers in some cases; while sensitivity assessments tend to look more closely at biological/ecological responses (traits) of marine species (e.g., phenology, abundance and distribution). Yet, the results are useful for comparing the level of sensitivity/impact on one particular species amongst different marine organisms, allowing for a fuller picture of CC effects from different scientific angles.

3. Results

A total of 1047 articles were found in all the searches within the six library databases, which was further reduced to 180 articles after

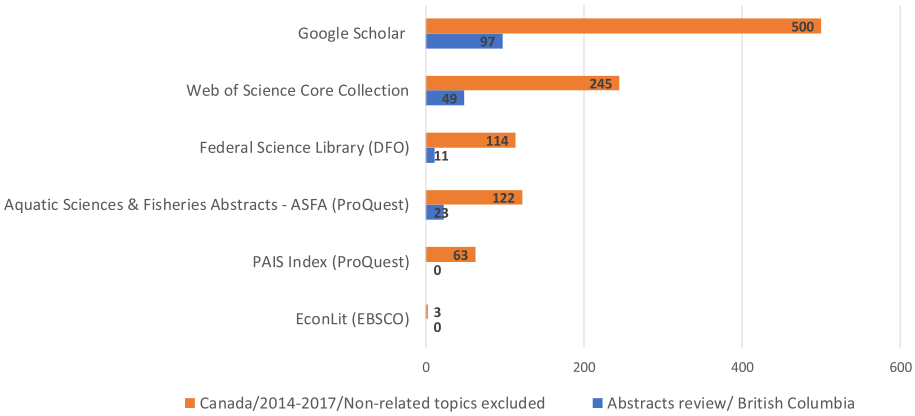
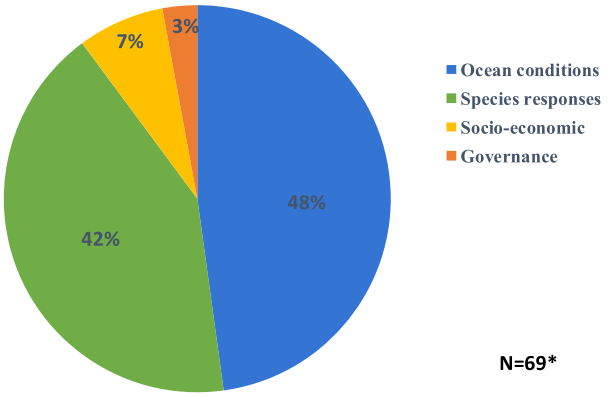


Fig. 2. Search results from library databases.



*The sample was further reduced after excluding repeated articles between library databases.

Fig. 3. Articles re-arranged by subject areas.
*The sample was further reduced after excluding repeated articles between library databases.

excluding all duplicates between searches (Fig. 2). More than half of the articles were found using the search engines from Google Scholar and Web of Science. The remaining articles were found in specialized libraries, such as the Aquatic Sciences & Fisheries Abstracts (ASFA) and the Department of Fisheries and Oceans (DFO) from Canada. No additional studies were found within the social science-based index databases, such as PAIS and EconLit (Fig. 2), which was not surprising due to the 'natural science' scope of Searches 1, 2, and 3. However, the lack of results for Search 4 and 5 in these library databases are consistent with research gaps on the socio-economic and governance components of Canadian ocean resources reported by Cisneros-Montemayor et al. [33].

The articles identified from all searches (after refinement) were organized and re-arranged according to four topics that capture the cascading effects of climate change in the oceans (Fig. 3). Since the search included anadromous species (e.g., Pacific salmon, eulachon) there are other sub-topics related to hydrologic regimes, such as water discharge and stream temperatures, which were included in the Ocean conditions section. The distribution of articles according to these topics are presented in Fig. 3, and clearly shows how scientific knowledge is prevalent in areas such as Marine species responses and Ocean conditions. As for the Socio-economic and Governance areas the number of articles found were significantly lower than the first two areas, which is consistent with previous findings (see above). Despite the disproportionate differences between the number of natural and social science-based articles in this region, there are increasing collaborative efforts to integrate biophysical and socio-economic indicators for understanding climate change impacts. These efforts have been made, especially, for global studies [18–20], but now increasingly carried out at the local level too [28,29,34], as reported in this study.

Shifts in temperatures (ocean and rivers) and stream flow were the most common environmental stressor covered by the studies included in the literature review, with significant knowledge gaps related to ocean acidification, deoxygenation and sea level rise impacts on marine species (Table 4). In addition, a wide range of species —over one hundred— were covered by one or more scientific articles in this literature review. Marine species of economic importance, such as, Pacific Halibut, prawns, crabs, tunas, sablefish, rockfishes were covered by at least five different studies, while Pacific salmon was by far the most studied species in BC —over twenty articles focusing on Pacific salmon. Regarding the areas studied by the articles included in this review, most of them focus on the Salish sea (southern/interior of BC) and the rivers systems that provides habitat for Pacific salmon. Significant knowledge gaps were found in areas of northern BC with only few studies covering the area.

Table 4
Number of studies available by type of threats, species and area.

	Number of Studies	
Threats	Temperature	**23**
	Streamflow/runoff	**10**
	pH	**6**
	Oxygen	**5**
	Sea level	**1**
Marine Species	Pacific salmon	**20**
	Pacific Halibut, prawns, crabs, tunas, sablefish, rockfishes	**4-7**
	Other species	**1-3**
Areas	Strait of Georgia/Salish sea	**29**
	BC rivers	**21**
	Open ocean	**18**
	West coast of Vancouver Island	**12**
	Northern BC	**11**

3.1. Ocean conditions

In BC, sea surface temperatures (SSTs) have increased since 1935 [35], although, warming trends are different depending on seasons, areas —south-north, inner/off coast— and data availability —time frame and lighthouse data selection. For example, warming trends increase in spring and are strongest in the summer [35]. At the same time, Amos et al. [36] report that there are significant differences in SSTs between northern and southern areas of BC, with no significant warming trends in northern regions. On the other side, the southern region shows an increase of up to 0.56 °C per decade[1] (1973–2010), which is expected to rise by 3 °C by the end of the 21st century [36]. In general, simulation of future oceanic conditions estimates that the average seasonal SSTs along the continental shelf of BC are predicted to increase between 0.5 and 2.0 °C for the period 2065–2078 [37].

In addition to ocean warming, changes in fresh-water conditions, e.g. temperatures, timing, discharge levels can also have negative impact on marine species. Water temperatures in the Fraser River warmed during the summer at a rate of 2.2 °C between 1953 and 1998 [35]. There is a growing number of scientific literature reporting that river temperatures [38], magnitude [39] and timing in river discharge [39–41] are all being affected by shifts in glacier mass balance [42], mountain snow packs [41,43] and permafrost [44] due to long-term changes in air temperature. There is an increased number of scientific studies (see Section 3.2.1.) showing the connections between these changes and physiological stress responses, behavioral shifts and decreases in the survival rate of Pacific salmon [45–47].

Ocean acidification (OA) is also considered an important threat to marine species of Canada's Pacific marine ecosystem [26]. The Northeast Pacific region is more exposed to OA than other regions because its waters have naturally low pH. At the same time, pH values can be highly variable in some areas, depending on several physical drivers, such as wind speed, freshwater flux, and cloud fraction [48]. For example, coastal upwelling in the West Coast of Vancouver Island (WCVI) brings waters high in dissolved inorganic carbon (DIC) to the surface mixed layer, lowering pH at shallow depth above 125 m, while, upwelled waters are also rich in nutrients increasing primary production and pH [32]. According to Haigh et al. [32], both effects explain wide ranges of pH values (7.8–8.4) in the surface mixed layer along the WCVI. Similar ranges of pH values are found in the Strait of Georgia (SoG), with strong seasonal cycles—low pH in winter/high pH in summer— and strong inter-annual variability during spring and summer [48]. Unfortunately, there is limited data available on OA to support any trend or increase in both, open ocean and coastal waters, in the region [27,49,50].

[1] Monthly sea surface temperature data were reduced to annual mean values for the purpose of decadal trend analysis by averaging of the monthly data [36].

In Canada's Pacific Ocean, availability of dissolved oxygen (DO) is also highly dependent on seasonality and processes that control oxygen concentration during the year, such as physical mixing, deep-water renewal, and respiration of organic matter. This is the case of the SoG, where hypoxic upwelled waters from the Pacific Ocean are intensively mixed with shallow waters in the Haro Strait before entering the Strait of Georgia (SoG), limiting the potential of surface waters to reduce DO in the deep SoG [51]. Despite the buffering function of some areas (e.g., Haro Strait and Juan de Fuca) that prevents further reduction in DO, oxygen concentration has declined in the SoG at a rate of 0.45–1.3 μmol L^{-1} yr^{-1} since 1971, and is approaching thresholds of biological tolerance — for mid-depth pelagic species— at specific times of the year [51]. This decline is mainly attributed to changes from outside the Strait,such as wind-driven coastal upwelling from the Pacific Ocean, which brings hypoxic water onto the shelf [51]. Nevertheless, it is unclear whether in the future DO will further decline at this rate in the northeast Pacific Ocean, as this trend could be part of a natural cycle [51].

Changes in ocean currents can have significant effect on the productivity of marine organisms and dispersal of early life history stages [27]. In general, high currents improve circulation conducive to well-mixing areas linked to high biological productivity zones [27]. Significant shifts in poleward (winter) and equatorward (summer) currents along the coast of BC can alter abundance and distribution of plankton and other migratory species [27]. In addition, interactions between ocean current patterns and upwelling and downwelling winds may affect seasonal productivity during spring transition [27]. Global ocean models project changes in the magnitude and direction of regional winds, with coastal wind strengthening during the summer [27,52]. Increased coastal wind strength in the summer, along with increasing stratification (resulting from shifts in sea surface temperature) may have significant impact on coastal currents and upwelling strength and timing [27]. Groundfish and invertebrates can be greatly impacted when oceans currents changes and concentrate larvae in areas with deficient conditions for growth and survival [27]. Stronger winter winds in Northern BC may result in larger Haida Eddies, with significant ecosystem consequences given the nutrients and larvae that they export offshore [53].

Oceanographic and biological variability in the Northeast Pacific Ocean is strongly influenced by el Niño/La Niña Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Significant processes and ocean parameters (e.g., temperatures, stratification, precipitation, winds, productivity, and upwelling) can be understood from this ocean-atmospheric events [54]. Both phenomena have warm/cool cycles, although, they manifest at different time scales. For example, ENSO has a cyclicity of about 3–7 years, while PDO cycles are measured in decades, repeating 40–60 years [50,54]. The warm phase of ENSO (El Niño) brings warmer winters with less precipitation, while the cool phase (La Niña) is linked to cooler and wetter winters [35]. The PDO is a widespread pattern of sea surface temperature in the northern Pacific Ocean [35], with a cool phase that appears to have occurred since the late 1990's [35]. The predictability of climate variability is limited, especially, regarding El Niño events that are rarely predictable more than one season ahead [54]. In fact, recent studies have shown that ENSO events are being more difficult to predict since 2000 [55]. Currently, variability of both phenomena has increased, impacting sea surface temperature in the northern Pacific Ocean. For example, the PDO index shows a phase-duration of about 20–30 years, which appears to have been reduced to 5 years, recently [27]. Similarly, ENSO events may have become more frequent in recent years, with four of ten strongest el Niño events of the 20th century occurring since 1980 [35].

3.2. Marine species responses

British Columbia marine ecosystem is extremely diverse in its geomorphology, climate and oceanography [26,56]. Thus, manifestations of CC in the region and marine habitat are multifaceted. A vulnerability

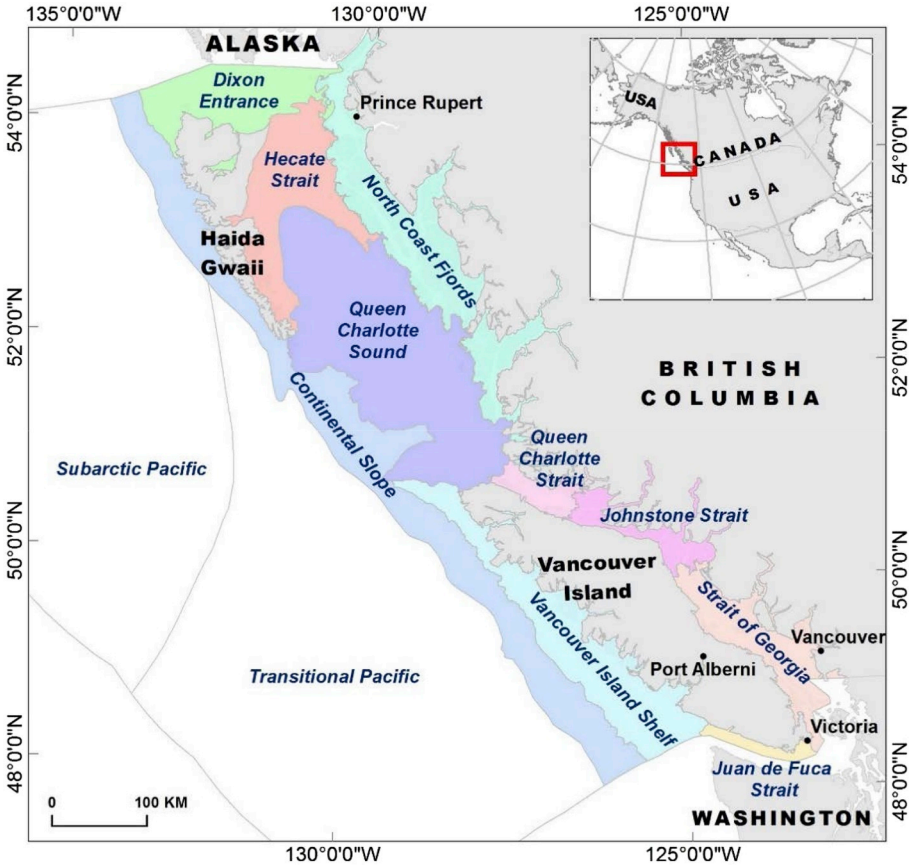


Fig. 4. Canada's Pacific coastal marine ecosections. British Columbia Land Use Coordination Office (MSRM, 2002). Map reproduced by Selina Agbayani, WWF-Canada, 2015. Figure from Okey et al. [91].

study in the region reports that the Strait of Georgia, the Queen Charlotte Strait, Juan de Fuca Strait, Vancouver Island Shelf, and Johnstone Strait (see Fig. 4) are the most vulnerable areas to CC in BC, with significant exposure to temperature change, acidity and ultraviolet radiation[2] [57]. In addition, the same study identifies shallow rocky reefs, seagrass habitats, kelp habitats, and deep rocky reefs, as the most vulnerable habitats in the region [57]. This study, also reveals that vulnerability in these areas are especially high due to cumulative impacts of human stressors [57].

3.2.1. Temperatures

Experimental and empirical research have studied how changes in river temperatures are affecting species survival and growth at multiple development stages. For example, scientific reports have shown that daily mean water temperature and discharge are correlated with sockeye salmon migration rates, having peak daily migration happening at relatively low water temperatures and high discharge levels [45]. According to Jeffries et al. [46], sockeye and pink salmon are exposed to physiological stress when temperatures are above 18 °C, increasing the risk of premature mortality of these species [46]. In fact, the high summer river temperatures are associated with adult sockeye mortality due to insufficient aerobic scope to support the fish's body functions above optimum temperatures during spawning migration up to the Fraser River [47].

In addition, Chen et al. [58] have indicated that temperature tolerance of sockeye salmon is linked to temperature conditions during egg incubation, and Whitney et al. [59] have shown a decrease in survival of some populations of sockeye salmon at embryonic development stages with temperatures of 16 °C —representing a future climate change scenarios. Changes in temperatures may also affect offspring competitiveness and development timing of sockeye salmon [60].

Shifting temperatures in the oceans also plays a critical role in mediating the bioenergetics of juvenile chinook salmon during times when food is scarce, with potential consequences in fish behavior and foraging ability [61]. According to Sharma et al. [62], changes in sea surface temperatures driven by shifts in local ocean conditions, such as El Niño/a events (ENSO) and Pacific Decadal Oscillation (PDO), have had a significant effect on survival of chinook populations from northern California to southeast Alaska. In addition, there has been a reduction in richness and changes in invertebrate community structure in the Salish Sea under warming-induced experiments [63]. Further, space occupancy and growth rates of intertidal species (e.g., barnacles) in Salt Spring Island have decreased under similar warming-induced experiments [64].

3.2.2. Ocean acidification and deoxygenation

Ocean acidification and deoxygenation may have a significant impact on marine species and fisheries [25,26,65,66]. Most of this knowledge in BC is based on experimental studies [32] conducted in laboratory, with few 'in-situ' studies [67]. Quantifying these impacts in the future is also difficult due to data limitations related to highly variable marine circulation [50] within a vast and diverse geographical and oceanographic setting [26].

OA in particular can greatly affect shellfish due to its direct impact on shell formation, especially, at the larval stage [32]. According to Haigh et al. [32], these impacts are already experienced in shellfish aquaculture in Southern BC and Washington state. In addition, species composition of phytoplankton and pteropods abundance may shift as a result of OA, triggering changes in the food web with potential consequences for finfish, such as pink salmon, and various species of rockfish and flatfish dependent on echinoderms [32]. Ultimately, there is also significant knowledge gaps on the direct effects of OA, especially, for highly lucrative species, such as the geoduck clam (wild and farming fisheries), Pacific halibut, Pacific salmon and prawn fisheries [32].

On the other hand, the literature suggests synergistic effects between multiple stressors (e.g., OA, hypoxia, shifts in temperatures, fishing) [32,65,66]. For example, a massive mortality of sea scallops was reported in 2013 in Vancouver Island, BC [68], probably due to abrupt changes in temperatures, low oxygen and variable pH [69]. Moreover, it has been shown that the effect of hypoxic waters in benthic community act cumulatively with other activities such bottom trawling, reducing species densities, richness and turnover at larger spatial scales [70].

3.2.3. Harmful algal blooms (HABs)

Shifts in the prevalence and distribution of HABs may have significant consequences for human health and deleterious economic effects for commercial and aquaculture fisheries, including public health costs and socio-ecological disruption [71]. Poisoning syndromes and impacts from HABs include paralytic shellfish poisoning, neurotoxic shellfish poisoning, and amnesic shellfish poisoning, amongst others [72]. Presence of HABs in the Salish Sea have been recorded over centuries [73], however, there has been significant increases in the potential growth rates and duration of these HABs events in BC and along the Alaskan coastline, between 1982 and 2016 due to ocean warming [74]. Empirical studies in the Salish Sea have confirmed that the greatest bloom risk lies between April and November (e.g., *Alexandrium*), with temperatures playing a key role in regulating its growth [73]. High levels of acidity are also making blooms of fish-killing alga (e.g., *Heterosigma akashiwo*) more frequent, and could boost the effects of neurotoxins produced by other harmful algae, impacting negatively salmon aquaculture and shellfish industries, respectively [32].

3.2.4. Sensitivity to climate change

Hunter et al. [30] provide an assessment of the sensitivity of 43 marine species to CC on the West Coast of Vancouver Island, using a vulnerability framework developed by Pecl et al. [75]. According to this approach, species that are more productive, with higher dispersal ability, and less dependent on seasonal environmental cues for key phases of their life cycle, are more resilient to climate change [30]. The results of this assessment ranked elasmobranchs (e.g., spotted spiny dogfish, longnose skate) as the most sensitive group to climate change, while flatfishes, such as rex sole and pacific halibut, being the least sensitive to CC [30]. On the other hand, ground fishes (e.g., sablefish, walleye pollock), invertebrates (e.g., geoduck, spot prawn), pelagic (e.g., Pacific sardine and albacore tuna) and rockfishes (e.g., yellowtail rockfish, canary rockfish), were groups with medium risk scores.

At a larger scale, important groups of species of economic importance are vulnerable to CC in the Pacific Large Aquatic Basin (LAB), including the West coast of Vancouver Island, the Strait of Georgia, and North coast of BC [27]. For example, changes in ocean stratification, current patterns, and primary productivity, could affect the ability of invertebrates and groundfish at early life stages to move or settle nearshore [27]. In addition, insights from observations of fish responses to extreme ocean conditions suggest that southern pelagic species could expand their migratory range, with potential increase in their abundance. Hunter et al. [27], also highlights the potential negative effects of OA on young fish, calcifying organisms, including indirect impacts on species in the lower part of the food chain.

3.3. Socio-economic of fisheries

In addition to climate impacts on marine biodiversity, anthropogenic CC can have severe consequences for society. For example, there is scientific evidence that reports the effects of climate change on the quantity and quality of marine fish catch and its distribution [2,17,18]. In turn, changes in fishing conditions under CC can lead to shifts in fishing costs, fish prices, fishers' incomes, earnings to fishing companies, discount rates and economic rent [2], compromising

[2] Studies on the impact of ultraviolet radiation (UV) on marine organisms have mostly focused on phytoplankton, zooplankton and higher trophic levels in marine ecosystems. These studies show that increased levels of UV affect photosynthetic activity, growth and metabolic rates, impair nitrogen assimilation, inhibit the motility and orientation of freely motile organism and bleach the photopigments (El-Sayed et al., 2007).

peoples' livelihoods and food security at global, national and local levels.

Shifts in stock distributions and fish abundance under CC will impact availability of marine resources in British Columbia. Canadians, in general, are important consumers of seafood compared to the global average [76]. However, less than one third (~18%) of fish caught in Canada are consumed locally, with the majority of Canadian catches being exported (~80%) [77]. According to Sumaila and Lam [28], around 60% of the total seafood consumption in BC is sourced from abroad. Therefore, socio-economic consequences of CC in the region are quite dependent on CC effects abroad, which poses some questions about food sovereignty in the region.

Sumaila and Lam [28], provide one of the first estimates of potential impact of CC in fish supply within the region, including projected changes in price for key marine species in BC This study reports negative changes under CC on seafood supply in species, such as sockeye and chum salmon, Pacific halibut, sablefish, Pacific hake, crabs and prawns. According to the authors, by 2050, sockeye, chum and sablefish stocks could drop by 21, 10, and 15 percent, respectively, leading to potential increase in prices for each of these species. Further, Sumaila and Lam [28] estimate that net changes in price for some BC marine species could result in extra household seafood expenditures of ~$110 million a year, under future CC conditions.

Other groups in BC, such as First Nations are highly vulnerable to changes in seafood availability as they depend on them for subsistence and ceremonial purposes. For example, for the 'Namgis First Nation, located in the northern end of Vancouver Island, species such as crab, clams, sockeye salmon and halibut, are part of their contemporary-traditional diet and are considered a yearly food need for a community of 1000 people [78]. Further, for Indigenous communities food represent more than nutrition itself, "it is a vital expression of continuance and identity" [78]. Therefore, becoming food insecure in the context of CC has major implications for Indigenous communities in BC.

Weatherdon et al. [29] have modelled the overall impact of climate change on abundance, distribution and catch potential for First Nations' fisheries within BC's marine environment. The results show a decline in abundance by up to −15% and catch potential by −4.5% for most of the sampled species, with projected poleward range shifts occurring at a rate of 10.3 km per decade by 2050, under a low greenhouse gas (GHG) emission scenario. In addition, the results show a positive correlation between changes in fish catches and latitude, with less severe declines in northern and central coast of BC than in southern coast. Besides, a strong negative correlation between species abundance and latitude has also been discovered. For example, Weatherdon et al. [29] report fewer number of species with declining abundance at higher latitudes.

In addition, coastal Indigenous communities are extremely vulnerable to sea-level rise because many reserves rely on subsistence fishing located in coastal lowlands [34]. For example, "salmon, clams, and other species that rely on the shoreline during one or more life phases are considered 'first foods', i.e., are an integral part of an extensive network of Coast Salish values, beliefs and practices" (p. 357). However, according to this study, nearly 75% of the 311 acres of intertidal zone and 3 miles of steep shoreline are at risk due to sea level rise [34].

3.4. Fisheries governance

Fisheries and their management have diverse range of options to respond to climate change effects such as switching target species, shifting fishing gears, moving to new fishing grounds, implementing marine protected areas, and exiting the impacted fisheries to look for alternative livelihoods [2]. However, the effectiveness of these responses to reduce climate risks will dependent on specific cases, local vulnerabilities and exposures to CC of the fishing sector. In addition, implementing harvest strategies that are determined/set with CC taken into consideration is an important step toward managing the combined (often synergistic) effects of fishing and climate change [79,80]. Finally, having effective fisheries management and regulations that are conducive to sustainability, along with reducing the impact of non-climatic anthropogenic stressors (e.g.

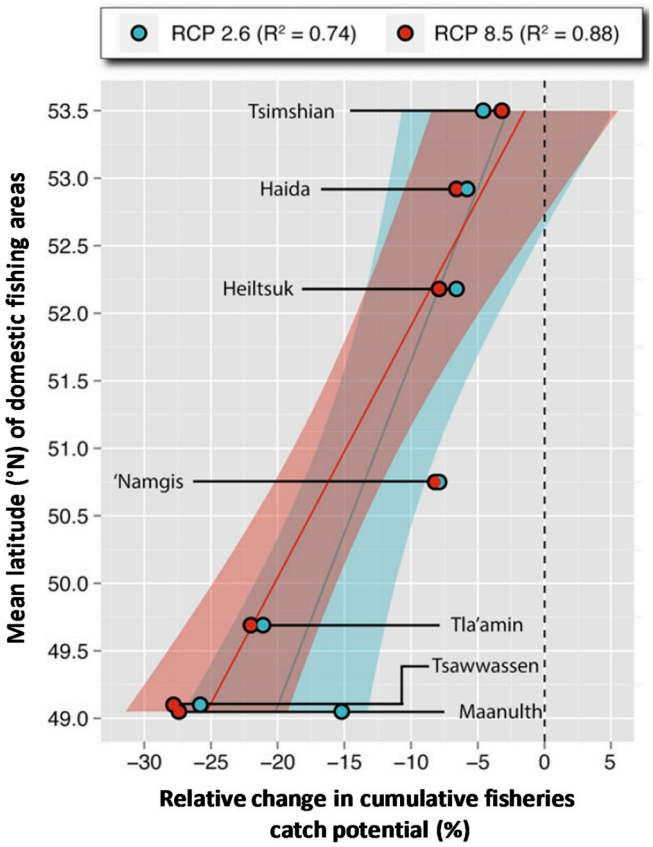


Fig. 5. Relationship between latitude and cumulative change in catch potential (%) by 2050, from the baseline (0%) under lower (RCP 2.6; blue) and upper (RCP 8.5; red) scenarios of climate change. Shaded bars represent 95% confidence intervals. Figure from Weatherdon et al. [29]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

dams, pollution, and habitat loss due to development) can result in BC fisheries being more resilient to CC [81].

Fisheries management challenges may arise due to the unequal distribution of relative loss in abundance and catches across different regions in BC (Fig. 5), such as implementing equitable resource sharing agreements amongst First Nations, redistributing access rights to fishing, and establishing joint-management initiatives to fulfill conservation objectives under CC [29]. Management strategies have been in place amongst First Nations to prevent future resource scarcity from seasonal or interannual fluctuations and long-term declines in abundance [29]. Spatial management, selective fishing and forms of mariculture, are some of the strategies used to manage species harvested by First Nations for food, social and ceremonial (FSC) purposes [29]. Reciprocal agreements used by First Nation to deal with resource scarcity has been based on the exchange of resources or access rights in single river systems rather than at the regional level [29]. However, CC scenario analysis [29] suggests a decline in abundance of all species in the Southern region of BC, challenging traditional management systems based on resource exchange or access rights amongst First Nations.

Managing transboundary fish stocks under changing climatic conditions can also be a challenging task, especially, due to potential conflicts that may arise amongst different countries fishing the same species [82]. A good example of this is the northeast Atlantic mackerel conflict that unfolded after sudden changes in distribution of this species after 2007 [83]. In North America, the Pacific sardine have also shown extreme fluctuations and geographic distribution due to water temperature regime shifts within the California Current Ecosystem (CCE) [84]. As a transboundary stock, Pacific sardines have been exploited by Mexican, U.S. and Canadian fisheries, and

conflicts are likely to arise amongst these countries because shifts in distribution of this species under cold and warm water regimes. Similar situations may arise for Pacific salmon and Pacific halibut fish stocks —both species jointly managed and regulated by the U.S and Canada— which are projected to move across national boundaries under future climatic conditions (Palacios-Abrantes et al. unpublished data).

Finally, structuring decisions for managing endangered species in a changing climate is another relevant topic in fisheries management. Gregory et al. [85], state that "climate change and other sources of uncertainties often block progress toward agreement on a management plan" (p.1220). Therefore, according to this study, it is important to develop a 'decision-focused' pathway for identifying key objectives and specific trade-offs, as well as comparing management alternatives. Further, the authors emphasize the need to evaluate climate change consequences, including uncertainties for managing endangered species under shifting climate conditions. Going beyond an exclusively science-based approach for protecting threatened species, this study proposes a structured decision-making (SDM) approach illustrated through several examples from Canadian fisheries, including the fisheries of BC.

3.5. Vulnerability and risk assessments synthesis (see Table 5a,b,c)

3.5.1. Finfish

Sensitivity to CC of flatfish is considered to be relatively low, with a few exceptions. For example, changes in environmental conditions, such as, shifts in temperatures, salinity and currents, can have a significant impact as phenological cue for spawning and breeding of arrowtooth flounder and dover sole species [30]. Low water temperatures [30] can limit the survival of larval/juvenile arrowtooth fish and its recruitment by altering the production of zooplankton [86]. In addition, dover sole species are highly dependent on specific habitat and prey (e.g., benthic invertebrate), which make them more sensitive to changes in the food web and ecosystems [30]. The overall risk of impact (exposure + vulnerability) to CC on flatfishes is considered to be moderate [31]. Nevertheless, changes in catches of this group are expected to be high with projected decline under changing climatic conditions [29]. Increasing acidification of the ocean may also affect flatfishes through changes in the food web (e.g., decline of echinoderms) [32].

Just like flatfishes, groundfish species are also dependent on environmental conditions (e.g., salinity, temperature, currents) as phenological cue for spawning and breeding [30]. For example, some groundfish species at the larval stage are exposed to significant variability in habitat conditions (e.g., temperature, upwelling-mediating seasonal timing), which may determine population recruitment [26,27]. Also, life-cycle events (e.g., spawning) of Pacific cod have a brief duration (e.g., Feb–March) with its development being strongly tied to temperature changes [30]. In general, the risk of impact to CC on this group is moderate [31], however, changes in catches of Pacific cod are expected to be significant in the future, with important declines under climate change [29]. Moreover, Pacific cod and lingcod are also susceptible to indirect impacts of OA driven by changes in the food web [32].

Pelagic species are especially sensitive to CC because recruitment events are highly episodic and spawning of this group is highly dependent on environmental cues (e.g., temperatures, plankton blooms, nutrient rich currents) [30]. For example, migration and spawning areas of Pacific hake stocks have expanded northward into Canada's

Table 5a
Summary table of sensitivity and risk assessments scores by group and species.

SPECIES				SENSITIVITY			RISK OF IMPACT	
				Okey et al. [26]	Hunter et al. [30]	Jones and Cheung [31]	Weatherdon et al. [29]	Haigh et al. [32]
	COMMON NAME	SCIENTIFIC NAME	ENVIRONMENT[a]	Species responses	Life history	Biology/Ecology	Catch Potential	Acidification
Flatfish	Arrowtooth flounder	*Atheresthes stomias*	demersal	**Low**	**Medium**	**Medium**	**High**	**Low**
	Dover sole	*Microstomus pacificus*	demersal	NA	**Medium**	NA	**High**	**Low**
	English sole	*Parophrys vetulus*	demersal	NA	**Low**	**Medium**	**High**	**Medium**
	Flathead sole	*Hippoglossoides elassodon*	demersal	**Low**	NA	NA	**High**	**Low**
	Pacific halibut	*Hippoglossus stenolepis*	demersal	**Low**	**Medium-low**	**Medium**	**Medium**	**Low**
	Petrale sole	*Eopsetta jordani*	demersal	NA	**Low**	**Medium**	**High**	**Low**
	Rex sole	*Glyptocephalus zachirus*	demersal	NA	**Low**	**Medium**	**High**	**Low**
	Southern rock sole	*Lepidopsetta bilineata*	demersal	NA	**Low**	NA	**High**	**Low**
	Yellowfin sole	*Limanda aspera*	demersal	NA	NA	NA	**High**	**Low**
Groundfish	Lingcod	*Ophiodon elongatus*	demersal	**Medium**	**Medium**	**Medium**	**Low**	**Medium**
	Pacific cod	*Gadus macrocephalus*	demersal	**Medium**	**Medium-high**	**Medium**	**High**	**Low**
	Sablefish	*Anoplopoma fimbria*	bathydemersal	**Medium**	**Medium-low**	**Medium**	**Low**	NA
Pelagic fish	Albacore tuna	*Thunnus alalunga*	pelagic-oceanic	**Low**	**Medium**	**Medium**	**High**	NA
	American shad	*Alosa sapidissima*	pelagic-neritic	NA	NA	**Medium**	NA	NA
	Capelin	*Mallotus villosus*	pelagic-oceanic	NA	NA	**Medium**	NA	NA
	Chub mackerel	*Scomber japonicus*	pelagic-neritic	NA	NA	**Medium**	NA	NA
	Jack Mackerel	*Trachurus symmetricus*	pelagic-oceanic	**Low**	NA	**Medium**	NA	**Low**
	Northern anchovy	*Engraulis mordax*	pelagic-neritic	**NA**	NA	**Medium**	NA	NA
	Ocean sunfish	*Mola mola*	pelagic-oceanic	**Low**	NA	**Medium**	NA	NA
	Opah	*Lampris guttatus*	bathypelagic	**Low**	NA	**Medium**	NA	NA
	Pacific butterfish	*Peprilus simillimus*	pelagic-oceanic	**Low**	NA	**Medium**	NA	NA
	Pacific hake	*Merluccius productus*	pelagic-neretic	**Low**	**Medium-high**	**Medium**	NA	**Medium**
	Pacific herring	*Clupea pallasii pallasii*	pelagic-neritic	**High**	**Medium**	**Medium**	**High**	**Medium**
	Pacific pomfret	*Brama japonica*	pelagic-oceanic	**Low**	NA	NA	NA	NA
	Pacific sand lance	*Ammodytes hexapterus*	benthopelagic	NA	NA	NA	NA	NA
	Pacific sardine	*Sardinops sagax*	pelagic-neritic	**Medium**	**Medium**	**Medium**	**Low**	**Low**
	Pacific surf smelt	*Hypomesus pretiosus*	benthopelagic	NA	NA	**Medium**	NA	NA

[a] [93] **Δ** For further details on the methods and scoring framework. See Table 3 and Supplementary Information

Table 5b
Anadromous and rockfishes.

SPECIES				SENSITIVITY		RISK OF IMPACT		
				Okey et al. [26]	Hunter et al. [30]	Jones and Cheung [31]	Weatherdon et al. [29]	Haigh et al. [32]
	COMMON NAME	SCIENTIFIC NAME	ENVIRONMENT[a]	Observation	Life history	Biology/Ecology	Catch Potential	Acidification
Anadromous fish	Chinook salmon	*Oncorhynchus tshawytscha*	benthopelagic	NA	NA	**Medium**	**High**	NA
	Chum salmon	*Oncorhynchus keta*	benthopelagic	**High**	NA	**Medium**	**Medium**	**Low**
	Coho salmon	*Oncorhynchus kisutch*	demersal	**High**	NA	**Medium**	**Medium**	NA
	Pink salmon	*Oncorhynchus gorbuscha*	demersal	**High**	NA	**Medium**	**High**	**Medium-high**
	Sockeye Salmon	*Oncorhynchus nerka*	pelagic-oceanic	**High**	NA	**Medium**	**High**	NA
	Eulachon	*Thaleichthys pacificus*	pelagic-neritic	**Medium**	NA	**Medium**	**High**	NA
Rockfish	Black rockfish	*Sebastes melanops*	reef-associated	NA	**NA**	**Medium**	**Low**	**Low**
	Bocaccio rockfish	*Sebastes paucispinis*	reef-associated	NA	**Low**	**Medium**	**Medium**	**Low**
	Canary rockfish	*Sebastes pinniger*	demersal	NA	**Medium**	**Medium**	**Medium**	**Low**
	Chilipepper rockfish	*Sebastes goodei*	demersal	NA	NA	NA	**Low**	**Low**
	China rockfish	*Sebastes nebulosus*	reef-associated	NA	NA	NA	**Low**	**Medium**
	Copper rockfish	*Sebastes caurinus*	demersal	NA	NA	NA	**Low**	**Low**
	Darkblotched rockfish	*Sebastes crameri*	bathydemersal	NA	**Medium-low**	NA	NA	**Low**
	Dusky rockfish	*Sebastes ciliatus*	demersal	NA	NA	NA	**Medium**	**Low**
	Longspine thornyhead rockfish	*Sebastolobus altivelis*	bathydemersal	NA	**Medium-low**	NA	NA	**Medium**
	Pacific ocean perch	*Sebastes alutus*	bathydemersal	**Medium**	**Medium**	**Medium**	NA	**Low**
	Quillback rockfish	*Sebastes maliger*	demersal	NA	NA	NA	**Medium**	**Low**
	Redbanded rockfish	*Sebastes babcocki*	demersal	NA	**Medium-low**	NA	**Medium**	**Low**
	Redstripe rockfish	*Sebastes proriger*	bathydemersal	NA	**Medium-high**	NA	**High**	**Low**
	Rougheye rockfish	*Sebastes aleutianus*	bathydemersal	NA	**Medium-low**	NA	**High**	**Low**
	Sharpchin rockfish	*Sebastes zacentrus*	bathydemersal	NA	**Medium-high**	NA	NA	**Low**
	Shortraker rockfish	*Sebastes borealis*	bathydemersal	NA	**Medium**	NA	**Medium**	**Low**
	Shortspine thornyhead rockfish	*Sebastolobus alascanus*	demersal	NA	**Medium-low**	**Medium**	NA	**Low**
	Silvergray rockfish	*Sebastes brevispinis*	demersal	NA	**Medium**	NA	**Medium**	**Low**
	Splitnose rockfish	*Sebastes diploproa*	bathydemersal	NA	**Medium-low**	NA	NA	**Low**
	Tiger rockfish	*Sebastes nigrocinctus*	reef-associated	NA	NA	NA	**Low**	**Low**
	Vermilion rockfish	*Sebastes miniatus*	reef-associated	NA	**Medium-high**	NA	**Low**	**Low**
	Widow rockfish	*Sebastes entomelas*	pelagic-neretic	NA	**Medium-high**	**Medium**	**Medium**	**Low**
	Yelloweye rockfish	*Sebastes ruberrimus*	reef-associated	NA	NA	NA	**Low**	**Low**
	Yellowmouth rockfish	*Sebastes reedi*	bathydemersal	NA	**High**	NA	**Low**	**Low**
	Yellowtail rockfish	*Sebastes flavidus*	reef-associated	NA	**Medium**	**Medium**	**Medium**	**Low**

[a] [93]; **Δ** For further details on the methods and scoring framework. See Table 3 and Supplementary Information.

Pacific waters since 1995 due to warming conditions [26], and the average latitude of Pacific herring and sardine spawning is affected by warmer sea surface temperatures [26,27]. In general, pelagic species have a high risk of impact to CC [31]. In particular, future catches of albacore tuna, Pacific herring, and sardine are expected to decrease by 2050 under CC, while sardine catches are projected to increase under future warming conditions [29]. Pacific hake, herring and sardine are also susceptible to negative impacts of OA, although there still a little understanding of how acidification may directly affect finfishes in BC [32].

There is a vast amount of scientific literature [46,47,58,59] that have shown stress responses of Pacific salmon above temperature threshold. Changes in river temperatures can also limit migration of spawning salmon, as well as, increase hatching mortality of this species [50]. However, there are high uncertainties about CC impact on salmon populations, due to multiple exposure to climate stressors during their life cycles, and wide range of sensitivities by life stage and habitat [87]. Also, eulachon spawning is sensitive to shifts in timing of spring freshet events, leading to earlier migration of this species to spawning grounds [26]. Sensitivity to CC of eulachon population may be exacerbated as they have experienced a long-term decline over the past 25 years attributed to fishing pressure and marine predation [26]. Like pelagic group, anadromous fish have a high risk of impact to CC [31], with projected declines in catches under future warming conditions for all the species included in this review [29]. In addition, juvenile pink salmon will be indirectly affected by OA, through changes in zooplankton biomass (e.g., pteropods) [32].

Few species of rockfishes have relatively high sensitivity to CC, such as, yellowmouth, widow, vermillion, sharpchin and redstripe rockfishes [30]. According to Hunter et al. [30], sensitivity levels of rockfish species are especially driven by infrequent recruitment, late age at maturity, and strong habitat affinity. Although, risk of impact assessment for this group is only available for some species, yellowtail, black, bocaccio and canary rockfishes, are known to be particularly impacted by CC [31]. In particular, future catches of redstripe species are expected to decline under CC by 2050 [29]. Moreover, the entire group may be indirectly impacted by OA, through changes in the food web, such as, decline of some echinoderms [32].

3.5.2. Invertebrate

3.5.2.1. Mollusc. Geoduck, Pacific oyster and Northern abalone are amongst the most sensitive species of this group included in the review.

Table 5c
Invertabrates and elasmobranch.

SPECIES				SENSITIVITY		RISK OF IMPACT		
				Okey et al. [26]	Hunter et al. [30]	Jones and Cheung [31]	Weatherdon et al. [29]	Haigh et al. [32]
	COMMON NAME	SCIENTIFIC NAME	ENVIRONMENT[a]	Observation	Life history	Biology/Ecology	Catch Potential	Acidification
Mollusc	Butter clam	*Saxidomus gigantea*	benthic	**Medium**	NA	**Medium**	**Low**	**High**
	Horse clam	*Tresus capax*	benthic	**Medium**	NA	NA	**Medium**	**High**
	Humboldt squid	*Dosidicus gigas*	pelagic	**Low**	NA	**Medium**	NA	NA
	Manila clam	*Ruditapes philippinarum*	benthic	**Medium**	NA	NA	**Low**	**High**
	Northern abalone	*Haliotis kamtschatkana*	benthic	**High**	NA	NA	**Medium**	**High**
	Olympia oyster	*Ostrea lurida*	benthic	**Medium**	NA	**Medium**	**Medium**	**High**
	Opalescent inshore squid	*Doryteuthis opalescens*	pelagic	**Low**	NA	NA	NA	NA
	Pacific cupped oyster	*Crassostrea gigas*	benthic	**Medium**	**Medium-high**	**Medium**	**Medium**	**High**
	Pacific geoduck	*Panopea abrupta*	benthic	**Medium**	**Medium**	**Medium**	**Low**	**High**
	Pacific littleneck clam	*Protothaca staminea*	benthic	**Medium**	NA	**Medium**	**Low**	**High**
	Pacific razor clam	*Siliqua patula*	benthic	**Medium**	NA	**Medium**	**Medium**	**High**
	Varnish clam	*Nuttallia obscurata*	benthic	**Medium**	NA	NA	**Medium**	**High**
Crustacean	Dungeness crab	*Metacarcinus magister*	benthic	**High**	**Medium**	**Medium**	**Medium**	**Medium-high**
	Green shore crab	*Hemigrapsus oregonensis*	benthic	NA	NA	NA	**Medium**	**Medium-high**
	Humpback shrimp	*Pandalus hypsinotus*	benthic	**Medium**	NA	**Medium**	**Very-high**	NA
	Humpy shrimp	*Pandalus goniurus*	demersal	**Medium**	NA	**Medium**	**High**	NA
	Northern shrimp	*Pandalus borealis*	demersal	**Medium**	NA	**Medium**	**Medium**	**Low**
	Purple shore crab	*Hemigrapsus nudus*	benthic	NA	NA	NA	**High**	**Medium-high**
	Red rock crab	*Cancer productus*	benthic	NA	NA	**Medium**	**Low**	**Medium-high**
	Sidestriped shrimp	*Pandalopsis japonica*	demersal	**Medium**	NA	**Medium**	**Very-high**	NA
	Smooth pink shrimp	*Pandalus jordani*	benthic	**Medium**	**Medium**	NA	NA	NA
	Spot prawn shrimp	*Pandalus platyceros*	benthic	**Medium**	**Medium**	NA	**Medium**	NA
	Tanner crab	*Chionoecetes bairdi*	benthic	**Medium**	**Medium-low**	NA	**Medium**	**Medium-high**
Echinoderm	Green sea urchin	*Strongylocentrotus droebachiensis*	benthic	**Medium**	NA	NA	**High**	**High**
	Pacific sea cucumber	*Parastichopus californicus*	demersal	**Medium**	**Medium-high**	NA	**Medium**	**High**
	Red sea urchin	*Mesocentrotus franciscanus*	benthic	**Medium**	**Medium-low**	NA	**Medium**	**High**
Elasmobranch	Spiny/piked dogfish	*Squalus acanthias*	benthopelagic	NA	**High**	**Medium**	**Medium**	**Low**
	Big skate	*Raja binoculata*	demersal	NA	**Medium**	NA	NA	NA
	Longnose skate	*Raja rhina*	bathydemersal	NA	**Medium-high**	NA	**Medium**	NA
	Salmon shark	*Lamna ditropis*	pelagic-oceanic	**Low**	NA	NA	NA	NA

[a] [93]; **Δ** For further details on the methods and scoring framework.See Table 3 and Supplementary Information.

For example, spawning and development of Pacific oysters are highly dependent on temperatures, and life cycle events of this species are short [30]. In addition, this group have small potential for geographical movement, which limit them to move to desirable habitat [30]. Geoducks also share with Pacific oysters some sensitivity traits, such as, brief duration of life-cycles events and low mobility. Also, recruitment events for geoducks are highly episodic, with a population age structure dominated by a few strong cohort [30].

Overall, the risk of impact to CC on this group are moderate, although, butter clam, Humboldt squid, Northern abalone and Pacific oyster have higher risk of impact [27,31]. In general, fishing catches for most species in this group are expected to decline, although, there is a few outliers (e.g., manila clam and geoduck), which expect an increase in their catches under CC by 2050 [29]. Most shelled molluscs are also likely to be impacted by OA [32]. According to Haigh et al. [32], negative effects of acidification may reduce calcification, growth and development in molluscs significantly.

3.5.2.2. Crustacean. Sensitivity of Dungeness crab, spot prawn and smooth pink shrimp stand out in this group, characterized by brief duration of life-cycle events. Dungeness crabs are sensitive to climate fluctuations, such as shifts in currents, waves, precipitation, temperature, runoff, and non-climate stressors [88], while warming conditions have led to northward expansion of smooth pink shrimp into Pacific Canada [26]. The overall risk of impact of CC on this group is moderate [27,31], although, negative changes in future catches are projected to be high for some species, such as, humpback, sidestriped and humpy shrimps [29]. Ultimately, Northern shrimp have exhibited delayed juvenile development at reduced pH, while studies on King crab and Tanner crab have shown significant vulnerability of these species at the early stages to OA [32].

3.5.2.3. Echinoderm. Like molluscs in general, echinoderms, have relatively low mobility [30]. Spawning of Pacific sea cucumber is highly dependent on environmental cues —triggered by periods of sunny days— and recruitment events of this species are highly episodic, which make this species particularly sensitive to CC [30]. Although, the risk of impact to CC on the ecology of this group is unknown, future catches on green sea urchin are expected to decrease under CC by 2050 [29]. As calcifying organisms, this group is directly exposed to OA effects, especially, at early life stages [32].

3.5.3. Elasmobranch

Spiny dogfish is the most sensitive species to CC assessed in the group followed by longnose and big skates. Elasmobranch, in general, have low fecundity, highly episodic recruitment events and reach sexual maturity at a later age, which make them very sensitive to climate fluctuations [30]. Unfortunately, there is very few information regarding the risk of impact of CC on this group except for dogfish species, which have one of the highest scores within all groups [31]. Potential catches for spiny dogfish are predicted to be negatively impacted by climate change in the region by 2050 [29], while OA may also have negative impacts on this species [32].

4. Conclusion

Important drivers of climate change in the ocean and marine species are temperatures, ocean acidification, and deoxygenation. Records indicate significant changes in sea surface temperatures in BC, with important differences according to areas and seasons [35,36]. In addition, the North East Pacific Ocean is naturally exposed to important levels of acidity, although, ocean acidification in the west coast of Vancouver Island and the Strait of Georgia are particularly variable, showing a wide range of pH values [32,48]. Also, oxygen concentration has declined in the deep Strait of Georgia despite the buffering function of natural processes, such as physical mixing and deep waters renewal, that prevent the Strait of Georgia from hypoxia [51]. Along with changes in Canada's Pacific Ocean, fresh-water conditions are also experiencing important transformations. For example, temperature, timing of discharge, and streamflow are being altered by long-term shifts of glacier mass balance, mountain snow packs and permafrost [41–43].

Some areas and marine habitat in BC are more vulnerable than others to CC impacts [57]. Vulnerability of Canada's Pacific eco-regions and marine habitat is associated with areas of high impacts of human stressors, such as the Strait of Georgia, Queen Charlottes Strait, Juan de Fuca Strait, Vancouver Island Shelf and Johnstone Strait [57]. According to vulnerability assessments, elasmobranchs and some rockfish species are amongst the most sensitive species to CC in the west coast of Vancouver Island (WCVI) [30]. Other group of species, such as groundfish and invertebrates are also quite sensitive to CC in the WCVI [30]. Pacific salmon species are also vulnerable to CC, due to their exposure to multiple habitats and climate stressors (e.g., marine and fresh-water). Changes in BC's water temperatures (e.g., ocean and river) are affecting pacific salmon migrations, growth and survival at different development stages [45,46,60]. In addition, ocean acidification (OA) may have indirect effects in pink salmon, through changes in the food web [32].

OA is likely to have negative effects on naked and shelled pteropods, shellfish aquaculture, echinoderms, and wild clam fisheries in BC, with subsequent effect on marine species dependent on echinoderms, such as flatfishes and rockfishes [32]. In addition, harmful algal blooms associated with changes in temperature and acidification have increased in the last years [32,74].

Shift in stocks distributions and fish abundance will impact fish supply affecting livelihoods and food security of British Columbian [28]. Local consumers in BC are predicted to be affected through changes in seafood price, which are likely to increase for some species, such as sockeye, halibut, and sablefish under future climatic conditions [28]. The impact of CC on overseas fisheries will also matter, as seafood consumption in BC is highly dependent on fish supply from abroad. Also, Indigenous groups are likely to be impacted by changes in abundance and catch potential of species of economic and cultural importance to First Nations [29]. The magnitude of these impacts will vary according to a latitudinal gradient [29]. In addition, it is expected that sea level rise will change intertidal zones and shorelines within First Nations territories in BC,having indirect impact on Indigenous communities health [34].

There is no silver bullet in fisheries management for addressing CC impacts on marine ecosystems and fisheries [89]. Management tools and adaptations plans may vary depending on specific levels of exposure and vulnerability of marine species, habitat and fishery sector. Unequal distribution of relative loss in abundance and catches across the region are one of the most important challenges for fisheries governance and management, especially, for Indigenous groups and territories located in southern areas of BC [29]. In addition, geographical distribution of transboundary stocks, such as Pacific sardine, Pacific salmon, and Pacific Halibut are likely to shift (Palacios-Abrantes et al. unpublished data), becoming a potential source of conflict between the U.S and Canada. Ultimately, it is important to consider climate change consequences and other sources of uncertainties, when managing threatened and endangered marine species [85].

4.1. Gaps and future direction of research

We have summarized in Table 6. Some of the most important gaps described by the studies covered in this literature review. First of all, the results of this work have shown that more knowledge is needed to fully understand the socio-economic consequences that CC may have on fisheries, fishers, and local communities. As we mentioned some work has already been done in this direction, showing the potential changes that CC may trigger on First Nations fisheries and British Columbian in general [28,29]. However, more effort is needed to complement this work including other important fishing sectors of BC, such as commercial and recreational fisheries.

In the management side of fisheries, some gaps include managing species of conservation importance. In this regard, studies in BC tend to focus more on species of commercial importance (see Table 4), disregarding other species that might be endangered or at risk. Also, better knowledge is needed for understanding and managing invasive species that are predicted to play an important role under future climatic conditions [26,27,50]. There are also significant gaps related to understand current and future trends of ocean acidification [27,50,90], and their impact of species of economic importance (e.g., Geoduck, Pacific halibut and salmon) [32]. Similarly, there is a big knowledge gap regarding sea level rise and its potential effects on marine ecosystems and species, which is worrisome as sea level data indicates a significant increase in some areas of BC (e.g., Victoria and northern areas) [50].

The climate interactions with marine habitat are also poorly understood, as well, as the impact of these interactions on marine species [27]. Fisheries dynamics in the context of environmental variability and climate change is also a big component missing in understanding CC effects on BC's fisheries. In particular, more studies are needed to understand the effects of climate forcing on recruitment [27]. In term of coverage, we need a better understanding of how CC is affecting marine ecosystem and species in northern areas of BC, especially, when observation-based studies and modelling work, are showing poleward changes in marine species distribution. In addition, there is data limitation regarding ocean parameters (e.g., pH, deoxygenation) not only in the Strait of Georgia, but also in the North Coast and Gulf of Alaska sub-basins [27]. The complexities of the processes interacting with OA and deoxygenation —freshwater inputs, sediments, ocean mixing, transportations, currents— make future prediction of these parameters challenging, especially, in extensive areas [50]. Finally, several studies are pointing out toward the need to consider combined effects (synergistic) of multiple climatic stressors on marine species [27,32], highlighting the importance to develop a "multi-stressor" approach to understand interactions amongst temperatures, hypoxia, and OA, and their net effects on marine species [32].

Declaration of interest

The authors have declared no conflict of interest.

Table 6
Summary of knowledge gaps from the literature review.

	Knowledge Gaps
Socio-economic	- Very few studies on understanding the socio-economic consequences of CC -e.g. changes in the costs of fishing, revenues and jobs - Also, lack of understanding of potential impacts on seafood trade, food security, and shifts in patterns of seafood consumption in the region
Management	- A more complete understanding of spatial trade-offs associated with the redistribution of marine resources is needed (Weatherdon et al., 2016) - Gaps in knowledge and management for invasive species and unknown impacts on species that are of conservation importance (Hunter et al., 2015) - Incomplete understanding of harvest strategies available to manage marine resources accounting for CC effects
Ocean Acidification	- Significant knowledge gaps on direct OA effects, especially, geoduck clam (wild and farming fisheries), Pacific halibut, Pacific salmon and prawn fisheries (Haigh et al., 2015) - Modulation of ocean acidification by freshwater inputs and interaction with the sediments are poorly understood in coastal waters (Hunter et la. 2015) - We lack long-term records of pH (and carbonate system) in the Strait of Georgia (Riche et al., 2013)
Sea Level Rise	- No studies were found in this review exploring potential impacts of sea level rise on marine species or ecosystems. However, sea level rise is a major environmental concern, not only globally but also in this region (Vadeboncoeur, 2016). Coral reefs, sea grass meadows, kelp beds, rocky intertidal zones and estuarine communities are all critical habitat for marine species structured around sea level.
Ecology Biology	- Incomplete data on biological traits (life history) of marine species and incomplete understanding about the linkages between these traits and vulnerability to climate change (Jones and Cheung, 2017) - Lack of knowledge of climate-habitat interactions and resulting impacts on fish and invertebrates (Hunter et al., 2015) - Knowledge gaps on the effects of climate forcing on recruitment (Hunter et al., 2015)
Areas	- Lack of knowledge -e.g. ocean parameter monitoring- in the North Coast and Gulf of Alaska sub-basins (Hunter et al., 2015) - We found very few studies of CC impacts on marine species in Norther areas of B.C
Data Limitation	- Long data records and continuous time series of observations are needed to detect oceanographic and biological trends (Hunter et al., 2015) - Future trends in oxygen concentrations and calcium carbonate saturation states in open ocean subsurface waters (including their transport onto the continental shelves) are poorly understood (Hunter et al., 2015)
Cumulative Synergistic impacts	- Lack of understanding on the combined effects of multiple climate stressors on marine species (Okey et al., 2014; Hunter et al., 2015; Haigh et al., 2015) - Further knowledge is needed to understand cumulative impacts of climatic and non-climatic stressors through integrative quantitative analysis (Okey et al., 2014)

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Appendix A. Supplementary data

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